

First Quarterly Report  
for  
Solar Cell Contact Development  
(28 June 1968 - 28 Sept. 1968)

Contract No.: NAS5-11595

Prepared by  
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2003 East Hennepin Avenue  
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for  
Goddard Space Flight Center  
Greenbelt, Maryland



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## SUMMARY

The purpose of this report is to describe the technical progress accomplished during the first quarter of a 12-month research contract, No. NAS5-11595, for NASA-Goddard Space Flight Center. The contract objectives are twofold: (1) to identify the Ti-Ag contact degradation mechanism on Si solar cells and (2) to determine whether sputter deposition of contact material is compatible with present solar cell configurations. Contract effort during this reporting period was concerned with contact degradation studies only.

Degraded and non-degraded Si solar cells were subjects of a characterization study that employed a number of analytical tools. Among the tools were a high power optical microscope, an x-ray diffractometer, an electron microprobe, an Electron Mirror Microscope (EMM), and an Auger/LEED ultrahigh-vacuum system. Cell configurations include as-received, peeled, and 1° angle-lapped cells. The angle-lapped or sectioned cells expose the p-n junction and metal-semiconductor junction region.

Optical examination of the interface exposed by a peeled contact almost without exception shows pronounced interference colors as observed under white light. This observation is not expected from thin opaque metal layers and suggests that the metal layer (very likely Ti) has undergone some sort of chemical transformation to a more transparent material.

X-ray examination of Ti-Ag contacts reveals the presence of well-crystallized Ag but does not show evidence of crystallized Ti or any other compounds.

Electron microprobe analysis clearly demonstrates that Ti and also some Ag remain on the Si solar cell subsequent to peeling. The peeled contact, on the other hand, contains mostly Ag and a small amount of Ti while no Si is found, with the exception of very small quantities in localized regions.

EMM observations on as-received, peeled, and sectioned cells reveal some evidence of a dielectric charging behavior which, of course, is not expected from conducting metal layers. Charging appeared to be most pronounced on one non-peeled cell while less charging is noted in peeled cells. This is not completely understood at present but possibly the high EMM retarding field existing at the surface may tend to break down thin dielectric layers when not protected by the conducting layer of Ag.

Auger/LEED measurements on a degraded cell which has its contacts intact are in progress. Auger spectra have been recorded from the Ti-Ag contact pad subsequent to a number of sputter-stripping treatments. Auger peaks from Ag have been readily noted in Auger spectra in addition to a peak at 90 eV (Si)



and at 183 eV (believed to be either B or C1. Noise is limiting the sensitivity of these measurements and an effort is being made to reduce the noise level.

A number of additional experiments were performed on sectioned cells and also on non-sectioned cells. These include scribing experiments, surface relief features as determined by the Talysurf, potential probing of contacts, I-V characteristics, and power dissipation experiments. This work is described in some detail.

We conclude that the contact peeling problem originates within the Ti-Ag metallized contact and more than likely near the Ti-Ag interfacial region, if not within the Ti layer itself. The exact cause of contact peeling has not as yet been identified but evidence suggests the Ti undergoes some chemical transformation such as, for example, formation of an amorphous oxide or nitride of Ti. The contact peeling problem does not, on the other hand, appear to be due to failure at the Si-metal interfacial region.

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## SECTION I

### Introduction

Background.— One of the most serious problems currently encountered with NASA Si solar cell arrays is the power degradation that occurs during prelaunch storage. Similar degradation has also been reproduced at Goddard Space Flight Center by exposing Si solar cells to 95% relative humidity at 80°C. Degradation in this case proceeds at an accelerated rate. Power degradation has been directly attributed to the Ti-Ag contacts employed on Si cells. The contacts frequently lose their intimate bond to the underlying Si and this effect is characterized by contact peeling and blistering. Because replacement of defective cells is a very costly and time-consuming task, it is of utmost importance to determine the cause of contact degradation and to take corrective action. One of the objectives of this one-year investigation is to identify the cause of Ti-Ag contact degradation and to recommend to the industry guidelines for fabricating non-degrading Ti-Ag contacts for Si solar cells.

The second objective of this investigation is to determine the feasibility of using physical sputtering in the deposition of metal contacts to solar cells and includes the study of the effects of sputtering on the cell junction properties and the physical properties of the sputtered contacts.

Contract work to date has been concerned entirely with the study of contact degradation and it is the purpose of this report to present the first quarter findings.

Si solar cells in various stages of degradation were supplied to us by NASA-Goddard Space Flight Center. These cells are 2 cm x 2 cm n- on p-type Si with 6 Ti-Ag grid lines extending from the Ti-Ag ohmic strip contact as illustrated in Figure 1. The dimensions of the contacts vary somewhat among the cells and those shown are only typical values. The contacts are deposited by conventional evaporation techniques. A thin (500 to 5000 Å) film of Ti is deposited onto air-oxidized Si, the thickness of the oxide being extremely thin (20 to 50 Å). A relatively thick Ag film of the order of 1 to 10  $\mu$  in thickness is subsequently deposited on the Ti. A similar but large area Ti-Ag contact is also made to the bottom surface of the cell. The contacts are subsequently sintered for a few minutes in forming gas at ~600°C.

Scope of Work.— The scope of the work performed to date is illustrated in Figure 2, where the various techniques and tools which have been employed in this study are shown. Work has centered, for the most part, on cells which exhibit rather severe degradation, for it is felt that these cells will show the effects of degradation more clearly. In some cases cells which show little or no degradation have also been included for comparison purposes.

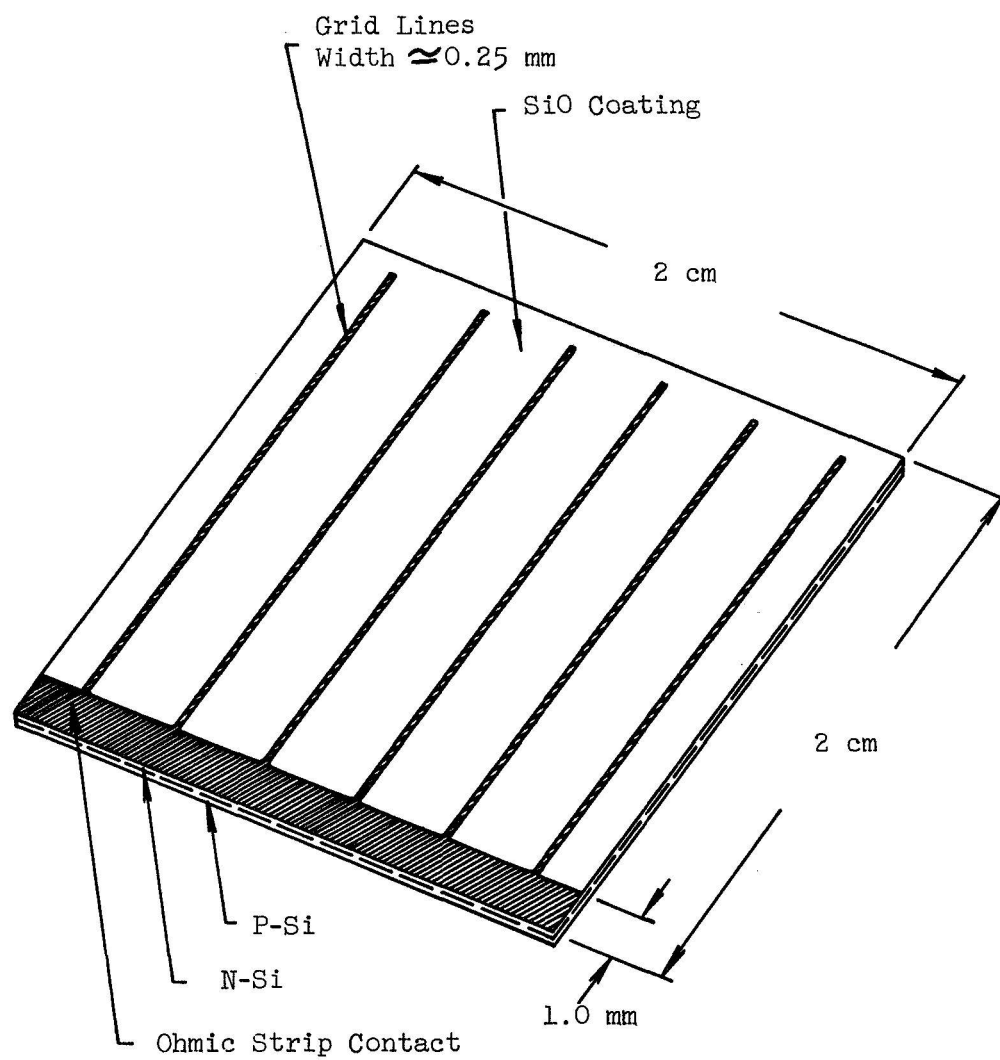


Figure 1 An illustration of a typical 2 x 2 cm Si solar cell with Ti-Ag contacts.

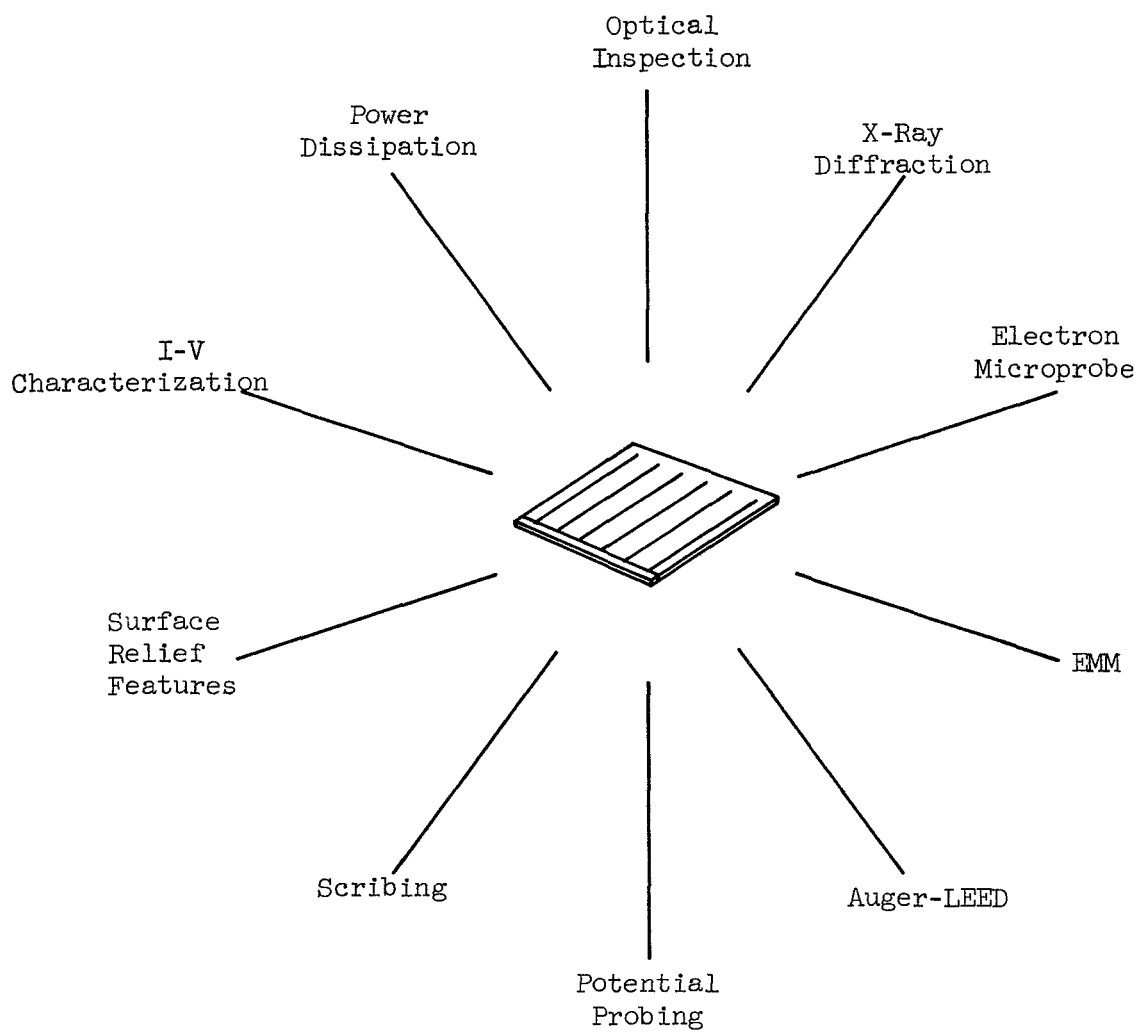


Figure 2 An illustration depicting the scope of work performed during the reporting period.

Our studies have been concentrated on Ti-Ag contacts found on the top or active surface of the cell, for these contacts are causing most of the problem; however, contact peeling is also observed to some degree on the bottom Ti-Ag contact. Some sectioned cells were also included in this work. These cells are 1° angle lapped to expose in depth the Ti-Ag contact, the junction of the metal contact to the Si, and the p-n junction.



## SECTION II

### Technical Discussion

Optical Inspection.— A number of cells were examined with the Reichert Optical Microscope under medium and high power magnifications. Both color and black and white photographs were taken to document this work. Only reproductions of a few black and white photographs are given here. Figure 3 was taken from a cell which has the Ti-Ag contact intact. The region of observation is where the grid line meets the ohmic strip contact. Note that the Ag overlayer has some structure in the form of a grainy-like appearance and this structure is found to propagate to the very edge of the contact. Examination of partially peeled cells suggests that the structure also propagates in depth throughout most of the metallized layer, as similar structure is frequently observed on the interface exposed by a peeled contact.

The exact origin of this structure is not presently known. It may possibly reflect an effect of stress that is released during cooling subsequent to the 600°C sintering treatment. Differences in thermal expansion coefficients could cause gross slip to develop in the metallized contact. The structure does not, on the other hand, appear to be due to single crystal grains separated by grain boundary because the grain size would be in the 10 to 50  $\mu$  range which is one to two orders of magnitude larger than observed in the x-ray diffraction studies reported later.

At somewhat higher magnification (450X), as shown in Figure 4, finer structure is noted in the form of small pits.

Optical examination was made on a number of cells that exhibited pronounced peeling tendencies and on cells whose contacts were intentionally stripped. Stripping was done with a razor blade and tweezer. Frequently the entire contact including the ohmic strip and grid lines is removed intact. It should be noted that all cells could not be intentionally stripped and this apparently reflects variations in the degree of contact degradation among cells. The most striking observation on peeled or stripped cells is the appearance of colors on the exposed surface of the cell as viewed under white light conditions. Frequently one or two colors are predominant over the interface such as shades of blue, brown, and yellow. At times, multiple interference colors are found. Examination of the exposed surface of the peeled contact normally shows a metallic appearance although there were exceptions to this.

The observation of colors at the peeled interface indicates the presence of a substance having a low optical absorption coefficient such as, for example, a metal oxide or nitride. Most metals including Ti and Ag have a high optical absorption coefficient and do not generally exhibit

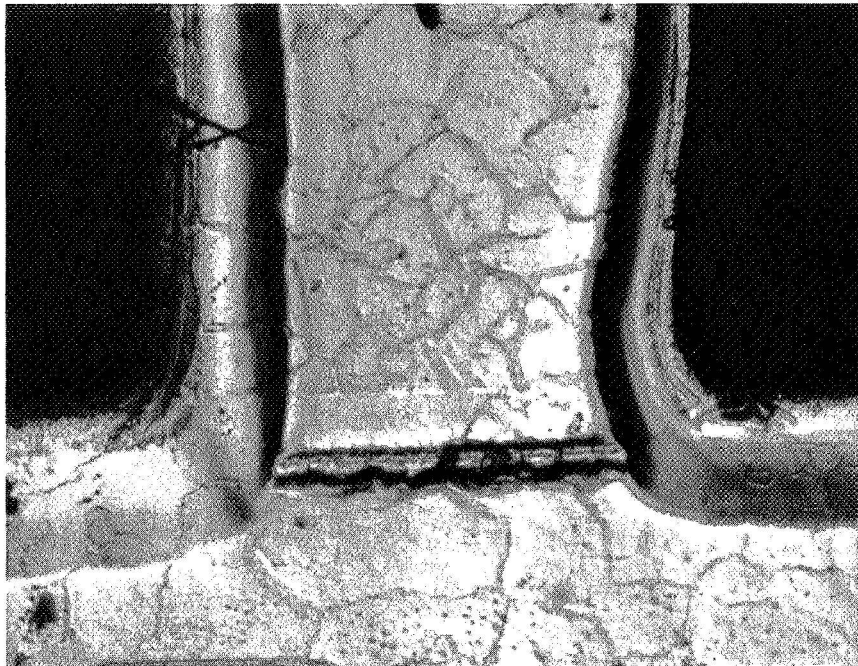


Figure 3 Typical appearance of Ti-Ag contact.  
Magnification is 150X.

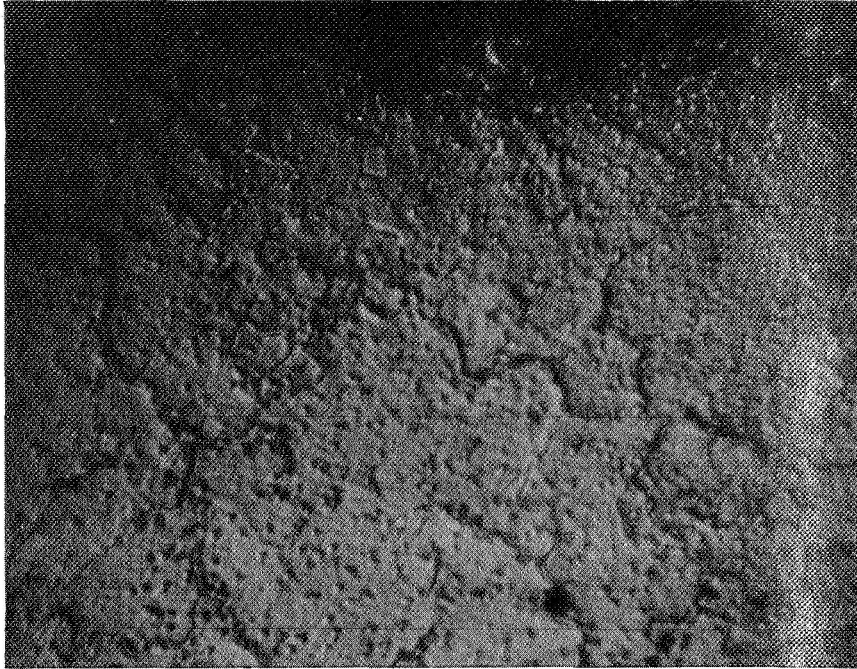


Figure 4 Fine structure is noted in the form of small pits. Magnification is 450X.

interference colors in thin film form. These results then suggest that some rather extensive chemical transformation may be taking place in the region of the contact where peeling occurs. The small amount of oxygen present in the form of  $\text{SiO}_2$  onto which the Ti is evaporated does not appear to be sufficient to explain these findings.

Close inspection of several cells subsequent to stripping found a portion of the contact still remaining on the cell, specifically at the edge of the Ti-Ag contact where it is overlapped with the SiO layer. Greater adhesion is apparently present here. Overlap with SiO does not always occur, as shown in Figure 5.

X-Ray Diffraction Studies.— X-ray diffraction is an invaluable tool for determining crystal structure and lattice constants of solids. The purpose of employing x-ray diffraction here was to identify the crystalline nature of Ti-Ag contacts. For example, if Ti and Ag retain their characteristic bulk crystalline structure, then x-ray diffraction should reveal this structure in the x-ray pattern. Similarly, well-defined intermetallic or other compounds of Ti or Ag also may be identified provided such compounds are sufficiently well crystallized.

Two common methods of x-ray diffraction were employed. In the first, a collimated beam of x-rays was made to impinge on the specimen under study (Ti-Ag contact) and the distribution of scattered x-rays was detected by film sensitive to x-rays. In the case of forward reflection, the incident x-ray beam was directed at a small angle with respect to the surface of the specimen ( $\sim 15^\circ$ ) as shown in Figure 6a and the forward-scattered x-rays were detected. In back reflection the incident beam was directed normal to the specimen surface as shown in Figure 6b and the back-scattered x-rays detected. Figures 7a and 7b show the forward- and back-reflection patterns, respectively, as taken from a Ti-Ag contact. A specimen-to-film spacing of  $\sim 3$  cm was used. In Figure 7a, two fairly well-resolved arcs are noted in addition to a number of elongated spots. It has been established that the arcs are characteristic of polycrystalline Ag, the inner arc being due to reflection from (111) planes while the outer arc is from (200) reflecting planes. A portion of a third arc can also be seen in the upper left-hand portion of Figure 7a and is due to (220) reflecting planes. The elongated spots are reflections from the underlying Si single crystal and show that the incident and diffracted beams can penetrate to some extent through the Ti-Ag contact. The diffraction arcs from Ag are not uniformly intense over a given arc and this is well-known to be an effect of preferred orientation, i.e., the Ag crystallites are not randomly oriented but possess some preferred orientation. There is evidence of some relatively large Ag crystallites (in the micron range), as observed from well-resolved spots that fall in the arcs. These are found predominantly where the arc is most intense. Some radial streaking is also noted here and is not characteristic of well-crystallized Ag, but reflects a variation in lattice constant of Ag. This

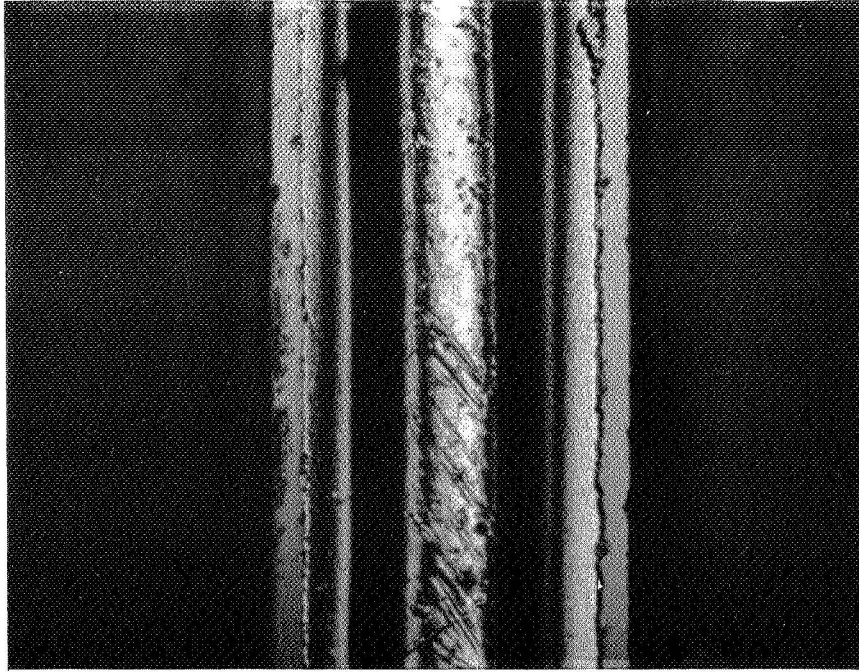


Figure 5 A Ti-Ag grid line that exposes Si on both edges of the contact. Magnification is 80X.

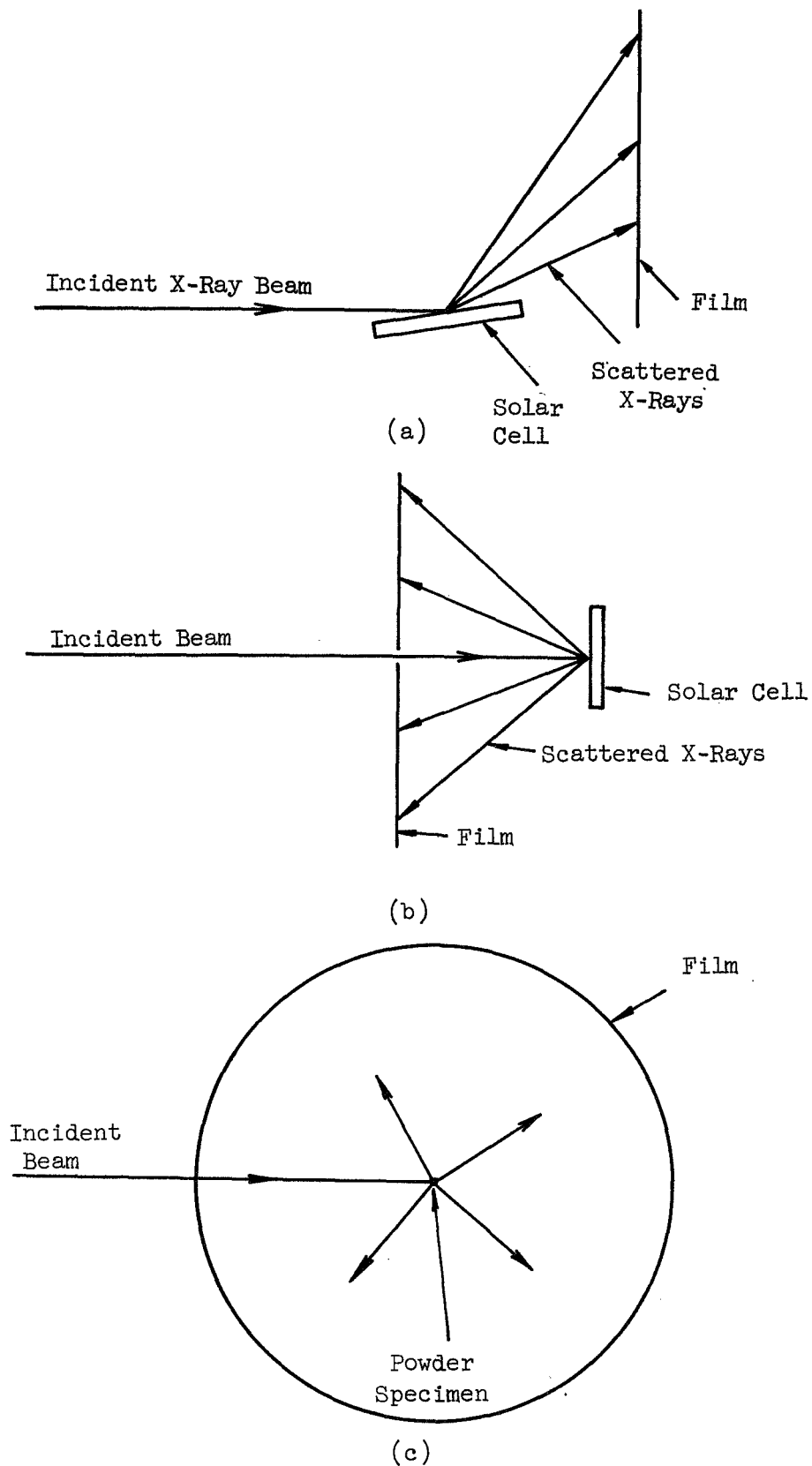
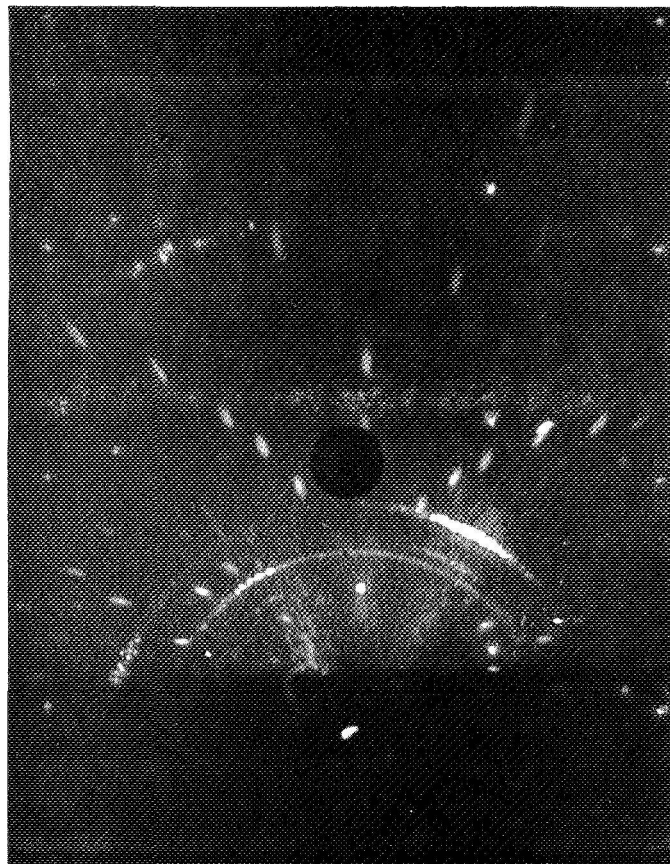


Figure 6 An illustration of (a) forward reflection, (b) back reflection, and (c) powder camera methods of x-ray diffraction.

(a)



(b)

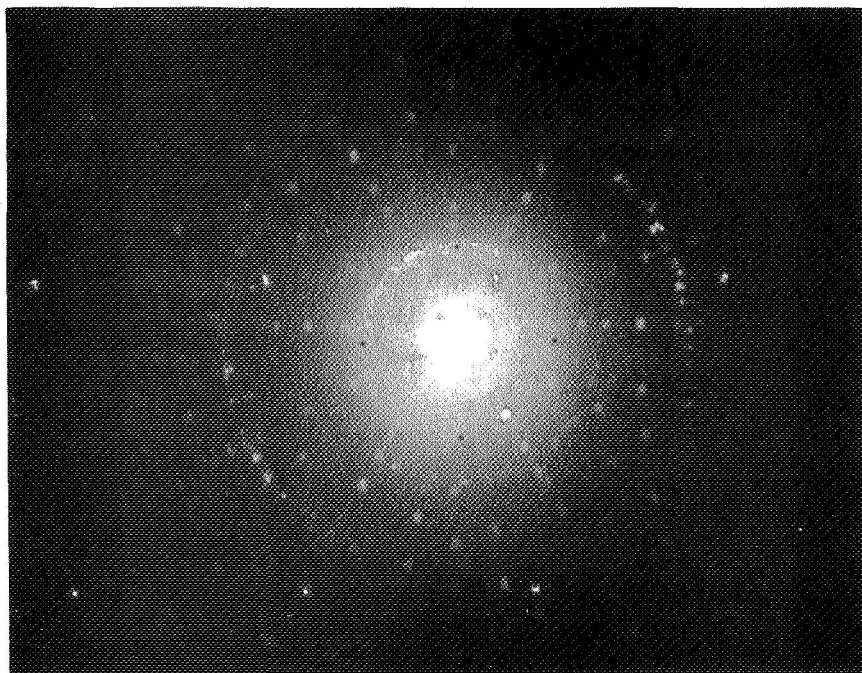


Figure 7 A Laue forward-reflection pattern is shown in (a); a back-reflection pattern in (b).

is very likely caused by strain present in the Ag layer. Strain can be of a mechanical nature or possibly an effect due to the incorporation of foreign atoms in the Ag lattice (Ti, for example). No direct evidence of Ti is found in the pattern.

The back-reflection patterns of Figure 7b show portions of several arcs and well-resolved diffraction spots characteristic of the (111) orientation of Si. The arcs again are reflections from Ag. No evidence of Ti is found.

The powder camera method of x-ray diffraction was the second method employed, as illustrated in Figure 6c. The purpose of using this technique was several-fold. First, the forward- and back-reflection techniques described above did not detect any crystalline Ti or any other possible compounds in the contact region and therefore it was of interest to note if this method could detect any. Second, only very small powder samples are required and this permitted samples to be prepared from the peeled interface region where Ti and possibly other compounds may exist. The powder camera method also gives more accurate measurements of the lattice constants.

Powder specimens were prepared by scraping material that remains on the solar cell subsequent to peeling. It was felt that this material should be rich in Ti or in compounds of the same. Samples prepared in this manner were mounted in the powder camera and exposed to x-rays for times of the orders of hours. A typical x-ray film is shown in Figure 8. All diffraction lines in this case are found to be characteristic of Si. Radial lines are also seen emanating from the exit port and are believed to be caused by lattice stress. No direct evidence of Ti metal or any compounds was found. It is not surprising that Si is seen here because it is known that some Si is removed from the cell during the scraping operation.

In summary, the x-ray results to date have identified the presence of crystalline Ag in the solar cell contact and also the underlying Si. It has not, on the other hand, detected any Ti in its bulk crystalline form, or the existence of any intermetallic or other compounds of Ti or Ag. It should be cautioned, however, that these results do not necessarily mean that there is no Ti metal or compounds present in the Ti-Ag contact, but only that they do exist in a sufficiently well-defined or crystallized state to exhibit characteristic x-ray diffraction effects.



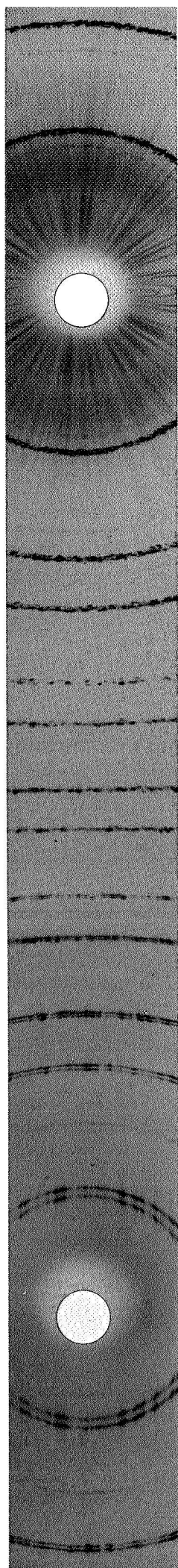


Figure 8 A powder camera pattern reveals characteristic Si lines and streaking about the exit port. Exposure time of 24 hr at 30 keV.

Electron Microprobe Analysis.— The electron microprobe is a sensitive analytical tool for detecting small quantities of materials by characteristic x-ray emission. A 20 keV electron beam having an extremely small diameter of  $2\ \mu$  impinges on the sample under study and produces x-rays when atoms, excited by the primary electron beam, return to their ground state. The sampling depth is of the order of several microns and is sensitive to all but the very light elements ( $Z > 12$ ). Unfortunately, elements such as hydrogen  $Z = 1$ , oxygen  $Z = 8$ , and nitrogen ( $Z = 7$ ) are very difficult to detect and even then special equipment is required.

A number of samples were analyzed by the electron microprobe at the University of Minnesota. Among these included solar cells with peeled contacts, the peeled contacts themselves, and several sectioned cells. The results of probing a peeled cell are shown in Figure 9. Here the characteristic x-ray emission response is shown for Si, Ti, and Ag at various random positions on the contact region of a peeled cell. Response for 100% Si, Ti, and Ag is also shown. In Position 1 the electron beam was just off the contact region and shows Si only. In most of the remaining positions some Ti and Ag are found--the exact amount varying with position. The Si response is less here because of the absorption in the Ti-Ag overlayer.

A peeled contact itself was also analyzed by the electron microprobe. In this case we find the exposed interface gave a strong Ag response and, in addition, a weak Ti response. The amount of Ti was in this case considerably less than that found on the interface of a peeled cell such as given in Figure 9. Several small areas were found, however, where an abnormally high Ti response occurred and interestingly these areas show a variety of interference colors. A very weak Si response was noted in only a few small, isolated regions.

Probing a sectioned cell is in progress and results will be given in the next report.

Electron microprobe analysis has confirmed our earlier opinion that contact peeling occurs somewhere within the Ti-Ag metallized layer and does not occur at the semiconductor (Si)-metal interface. This follows from the fact that a relatively large amount of Ti and some Ag remains on the solar cell subsequent to peeling. Microprobe analysis also shows that some mixing of Ti with Ag most probably occurs, for both components are generally observed on the two interfaces exposed by peeling. It also shows that peeling is complex in that the interface exhibits varying amounts of Ti and Ag. This behavior can explain local variations in optical appearance of the interface, e.g., in interference colors. Finally, these results tend to associate Ti with interference colors.

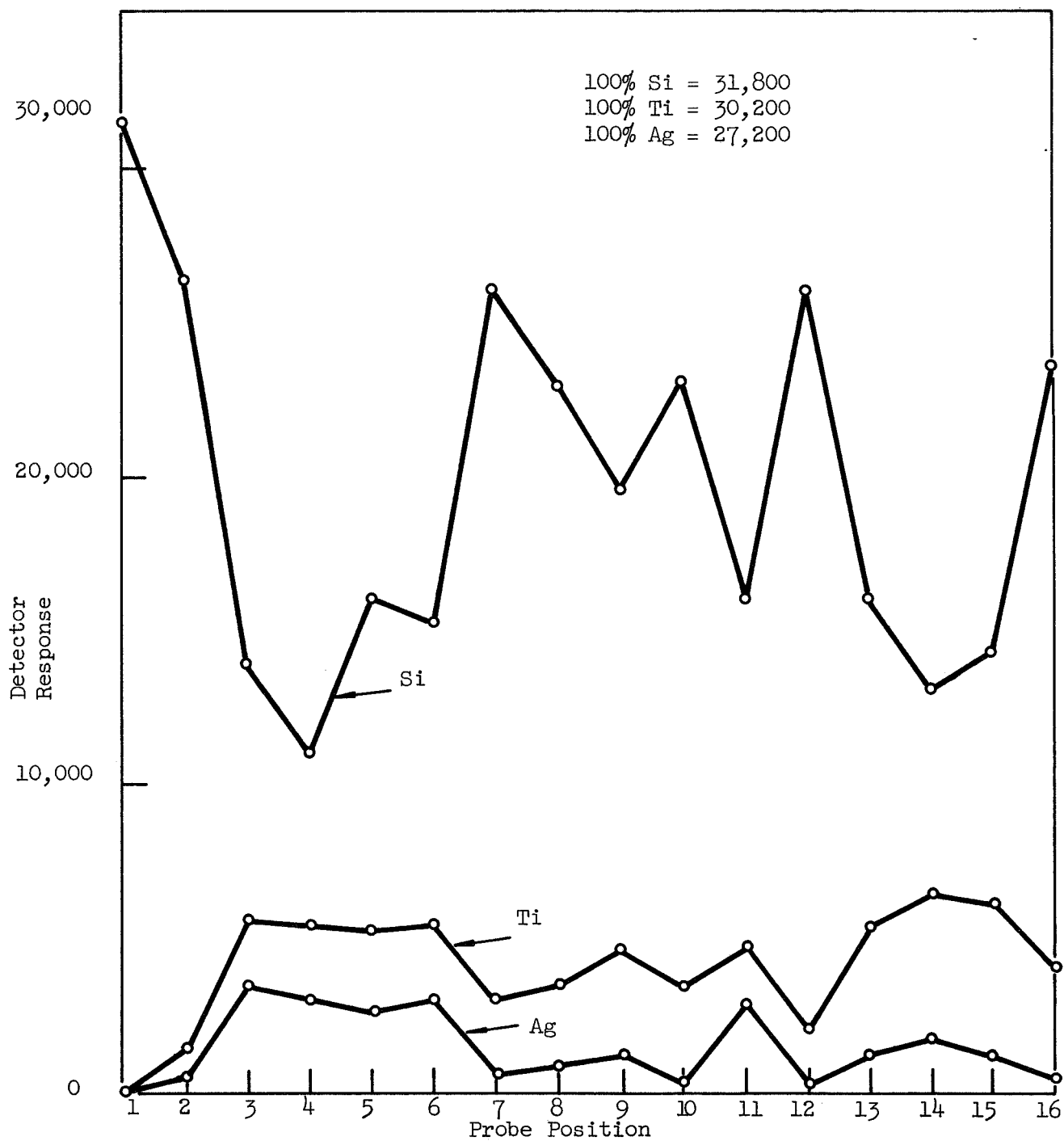


Figure 9 Electron microprobe results from a peeled cell.  
 Both Ti and Ag are found over most of the peeled  
 contact.

Electron Mirror Microscopy Studies.— The Electron Mirror Microscope (EMM) is a research tool sensitive to weak electric and magnetic microfields existing at a surface. A beam of electrons is directed at the surface of a specimen and, with a retarded field, is turned around just in front of the specimen. Surface microfields alter the electron trajectories and these are reflected in the spacial distribution of the electrons as they excite a fluorescent screen.

A solar cell with contacts intact was initially placed in the EMM for study. It was soon realized that the cell contacts exhibited an unusual property. By biasing the cell positive with respect to the cathode of the electron gun and thereby causing electrons to impinge on the cell, we found regions on the contact that charged up as good insulators will do.\* By biasing slightly negative, these regions retained their charge for times of the order of minutes. Figure 10a shows a region of a contact in the charged state. Figure 10b is the same region in the discharge state. Scanning the strip contact and grid lines revealed a number of these unusual regions. Subsequently several other cells have been examined in the EMM including a cell with peeled contacts and a sectioned cell. Some charging effects are seen with these cells but it is not nearly so evident.

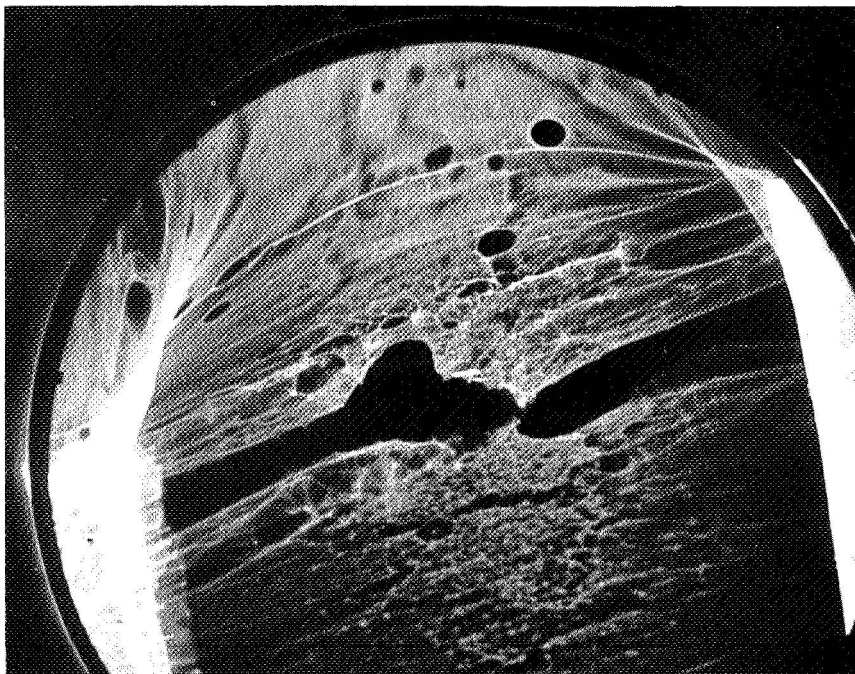
The origin of the charging phenomena is not exactly clear at this time although it definitely indicates the presence of some dielectric-like substance within the contact layer. It suggests possibly the existence of some foreign matter such as dust particles, residual photoresist, or possibly the formation of a dielectric compound of, e.g., Ti. We had expected a rather uniformly pronounced charging in the case of a peeled cell, if a dielectric compound was actually formed by Ti; but, as mentioned above, the charging behavior was not nearly so pronounced. Possibly the high electric field existing at the surface may, in the case of a peeled cell, break down the dielectric. Additional studies are required to clarify this point.

A sectioned cell was forward biased several amperes while viewing the p-n junction and metallized contact region. The voltage drop across the junction is readily discernible and although not highly conclusive as yet, there appears to be a small and abrupt IR drop in the metallized layer. This is observed by mechanically pulsing the current through the cell and noting the change in contrast of the EMM image.

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\*Since the time of this writing it was learned that the SiO layer is deposited onto the Ti-Ag grid lines. It may be that the charging phenomena described here is caused by this material.

(a)



(b)

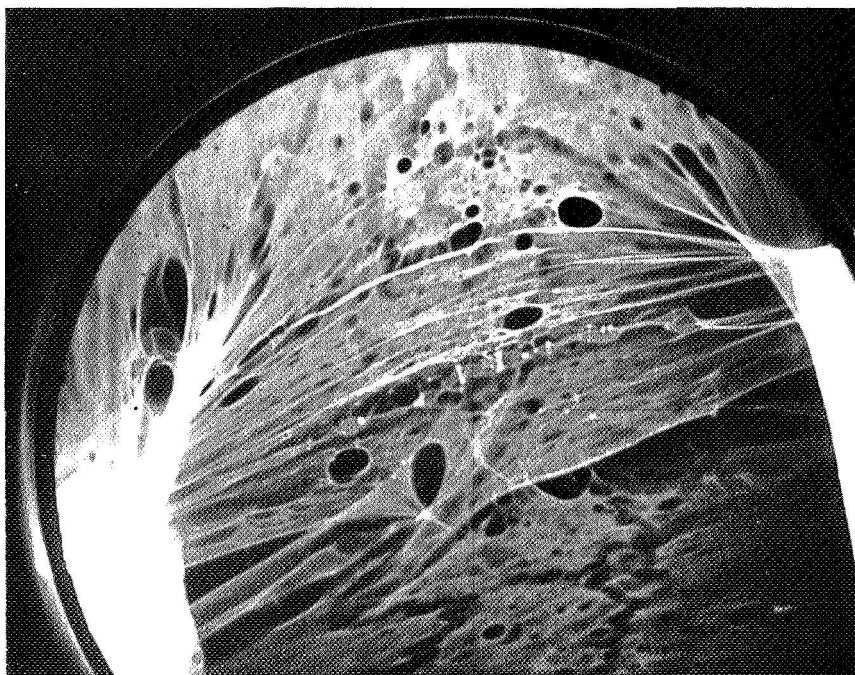


Figure 10 Evidence of charging is seen from the dark region which extends across the grid line in (a). The same area is viewed in (b) under a discharged condition.

Auger/LEED Studies.— A partially degraded cell with contacts intact was placed in the ultrahigh-vacuum, low-energy electron diffraction (LEED) system and Auger electron spectroscopy measurements are presently being made on the Ti-Ag contact. Auger spectroscopy is a rather new development in surface analysis whereby Auger electrons emitted from a surface under electron bombardment are used to identify the composition of the outermost few surface monolayers. Because Auger electrons possess well-defined energies characteristic of the material from which they originate, surface composition analysis can be realized by recording the energy spectrum of the emitted electrons. Harris<sup>(1)</sup> and more recently Weber and Peria<sup>(2)</sup> have described several practical schemes for measuring energy distribution spectra. We are using essentially the technique of Weber and Peria which employs a LEED tube.

The circuit employed in Auger measurements is shown in Figure 11. A 1500 eV beam of electrons is incident on the surface of the target under study (Ti-Ag contact) and creates a number of Auger electrons within the target. By applying a small sinusoidal voltage to the target, the kinetic energy of the ejected Auger electrons is likewise modulated. The outer grid is grounded and allows electrons with energies greater than some minimum value to pass through the grid and be collected on the fluorescent screen. The minimum electron energy is determined by the 0-750 V dc programmable voltage supply. The resulting ac current collected on the fluorescent screen appears as an ac voltage across the  $10^5 \Omega$  resistor which is subsequently amplified by the Princeton Applied Research (PAR) lock-in amplifier. The electron energy distribution curve,  $N(E)$ , is obtained by tuning the lock-in amplifier at the fundamental modulating frequency ( $\sim 200$  Hz) and recording the output of the amplifier on the Y-axis of the X-Y recorder while slowly scanning the programmable supply in the 0-750 V range. Auger emission is revealed as peaks that develop on the  $N(E)$  curve. Auger peaks are often small and difficult to detect on the  $N(E)$  curve and therefore the derivative  $\left(\frac{dN}{dE}\right)$  is generally recorded. This is simply done by tuning the lock-in amplifier to the second harmonic of the fundamental frequency and displaying its output signal on the Y-axis of the recorder as before.

The objective of the Auger measurements is to detect possible oxides, nitrides, or other likely contaminants in the Ti-Ag contacts. We have seen that electron microprobe analysis is not sensitive to the light elements ( $Z < 12$ ). Auger spectroscopy is, on the other hand, sensitive to the light elements. Harris<sup>(1)</sup> has tabulated Auger energies for a large number of elements. Palmberg and Rhodin<sup>(3)</sup> have looked specifically at face-centered cubic crystals such as Cu and Ag. Auger energies for a few elements of interest here are shown in Table 1.

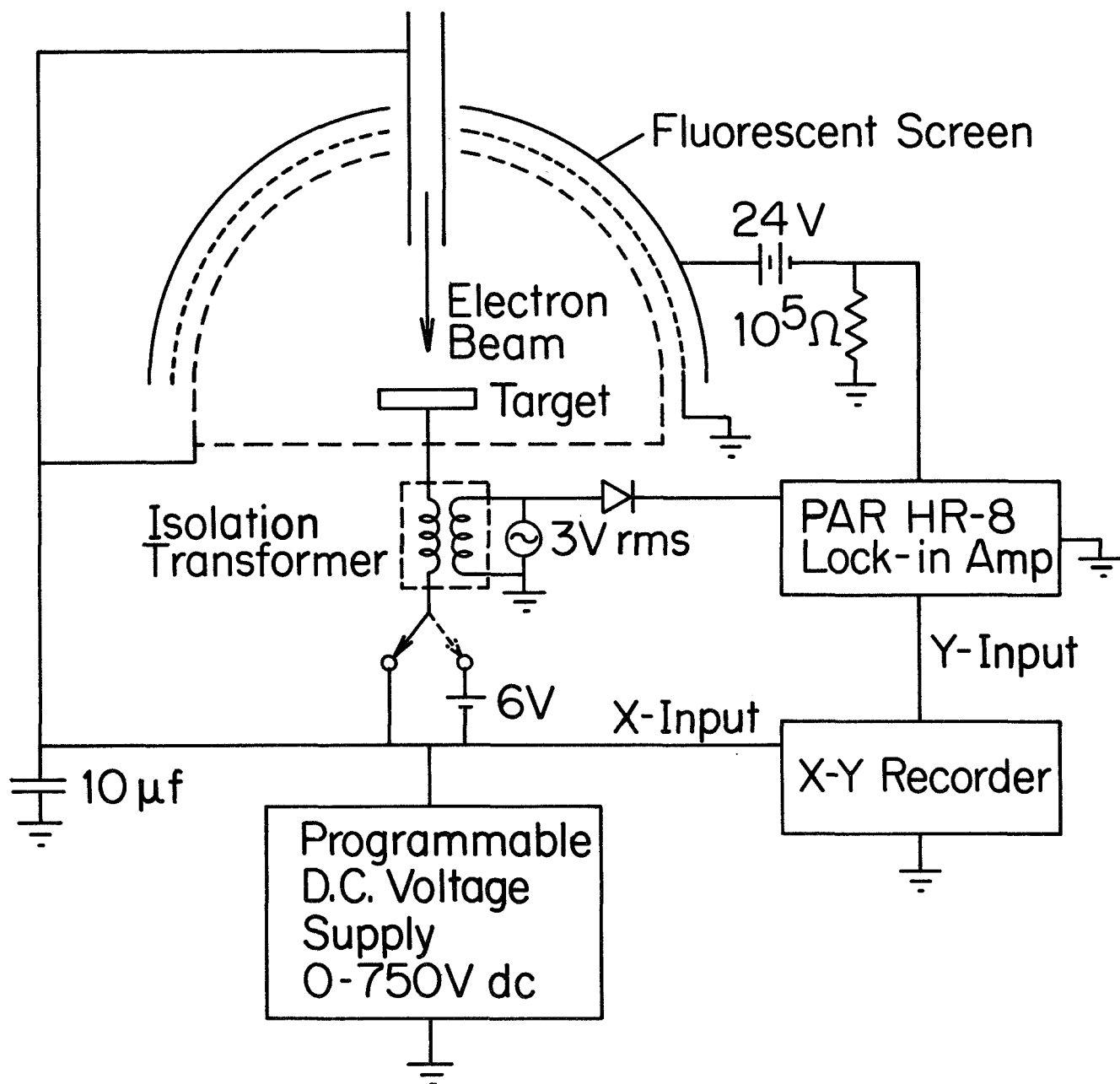


Figure 11. Circuit used in Auger electron spectroscopy measurements.

TABLE 1.—AUGER ELECTRON ENERGIES OF A FEW ELEMENTS

Element	Auger Energy (eV)
Ag	80, 268, 308, 362
Ti	~370, 415
Si	91, 1595
C	270
O	510
N	382
B	~180
Cl	~180

Figure 12 is an Auger spectrum from a Ti-Ag contact taken during the initial stages of this work. The solar cell with contact had been subjected to several low-energy Ar ion bombardments which served to clean the contact of residual impurities by sputtering. Reproducible structure was found in the spectrum of Figure 12, as verified by recording two or more times. Auger peaks at 77, 264, 300, and 357 eV (measured at the point of maximum negative slope) are due to Ag. Auger peaks are also seen at 90, 127, and 183 eV. The 90 eV peak is known to be due to Si, which is apparently back scattered onto the contact during the Ar sputter-cleaning treatments. The peak at 183 eV is believed to be due to either chlorine or boron.

The solar cell sample is presently being given a series of sputter-stripping treatments and the Auger spectrum is subsequently recorded in the region of the contact after each treatment. The purpose of stripping the contact is to sample the composition of the contact in depth for Auger spectroscopy samples only the first few surface monolayers. In this way it should be possible to obtain a composition profile, provided the sputter-stripping process does not seriously affect the surface composition. It is not clear at this time if sputtering affects the composition. Even if it does alter it to some extent, gross contaminants such as oxygen or nitrogen should still be evident.

Potential Probing.—Contact peeling is known to have a catastrophic effect on the electrical continuity of the solar cell contacts. It was of interest to determine whether contact degradation might be reflected in the electrical conductivity of the contact prior to peeling. Some potential probing experiments were performed on several cells for the purpose of evaluating the electrical properties of the Ti-Ag contacts. In one study a cell with contacts intact was forward biased at a voltage sufficient to pass,



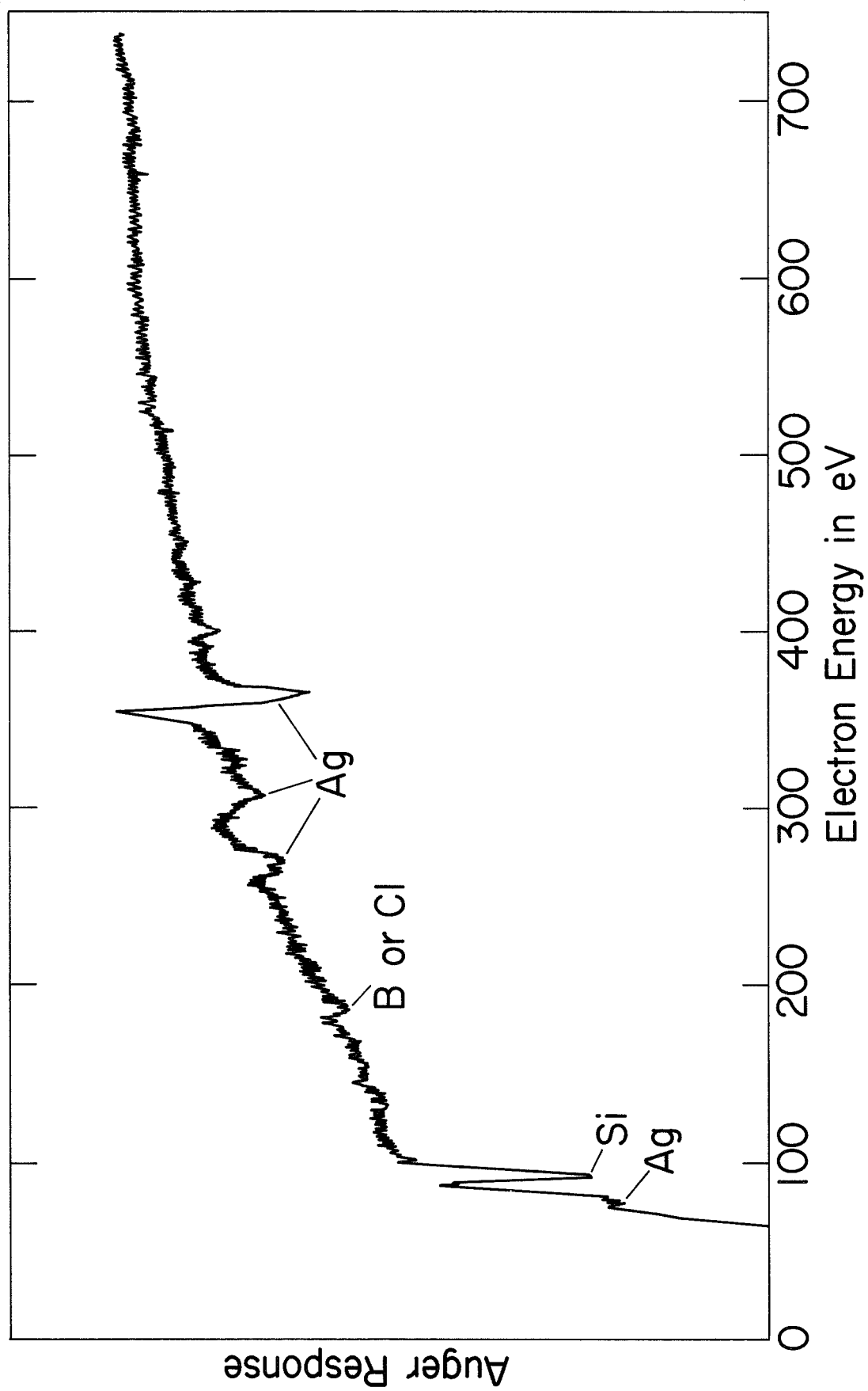


Figure 12 An Auger spectrum taken from a Ti-Ag contact subsequent to Ar sputter cleaning.

in one case, 1 A through the cell and, in a second case, 100 mA. The observed potential profile, as measured by probing the Ti-Ag contact with a fine wire, is shown in Figures 13 and 14, respectively. All voltages are expressed in millivolts. This particular cell exhibited a low effective series resistance of  $0.1\Omega$  as measured by the I-V characteristics. Several observations can be made from these figures. First, voltage drops do develop along the Ti-Ag ohmic contact strip and grid lines, although they are not excessively high in this case. Second, the voltage drop is not linear with distance but varies approximately as the square of the distance along the contact. It can be readily shown that this behavior is expected on theoretical grounds. Third, the resistivity of the Ti-Ag contact can be roughly estimated from the potential profile and contact dimensions. This turns out to be only a factor of three higher than that calculated under the assumption that contact is pure Ag.

Additional potential probing experiments on sectioned cells are in progress and will be reported in the Second Quarterly Report.

Scribing Experiments.— A few scribing experiments were made on a peeled cell for the purpose of evaluating the hardness of the residual contact material that remains on the cell. Initial work was done with a diamond scribe. Photographs of the scribed line that runs across a peeled contact are shown in Figures 15a (50 g load) and 15b (25 g load). Figure 16a (16 g load) was unusual in that it shows evidence of some folding back or peeling of the residual contact material. Figure 16b shows the result of scribing a number of times with a W probe at a load of 100 g. In this case the SiO layer is not affected while the scribe line appears to be seen in the contact region.

This work is in a very preliminary stage and therefore we do not wish to draw any conclusion as yet.

Surface Relief Features.— Optical studies, the electron microprobe results, and other findings have shown that a certain amount of contact material remains on the cell after the contact has separated by peeling. A surface relief study was conducted on the grid lines of one cell for the purpose of investigating the surface topography in the region of a peeled contact. A Taylor-Hobson "Talysurf" surface measuring instrument was employed in this study. The pick-up probe was scanned across a grid line at an oblique angle in order to expand the distance of travel. Figure 17 shows a typical recording taken at a sensitivity of 400 Å/div. A slight misalignment of the cell gives rise to the overall slope at this high sensitivity. The dashed line gives approximately the level of the underlying Si surface (as determined by drawing a line between the two points on the recording indicated by Si). This particular cell had Si exposed between the SiO and the Ti-Ag contact. Significantly more contact material is noted at the edge of the contact than in the central region. This finding is also evident in

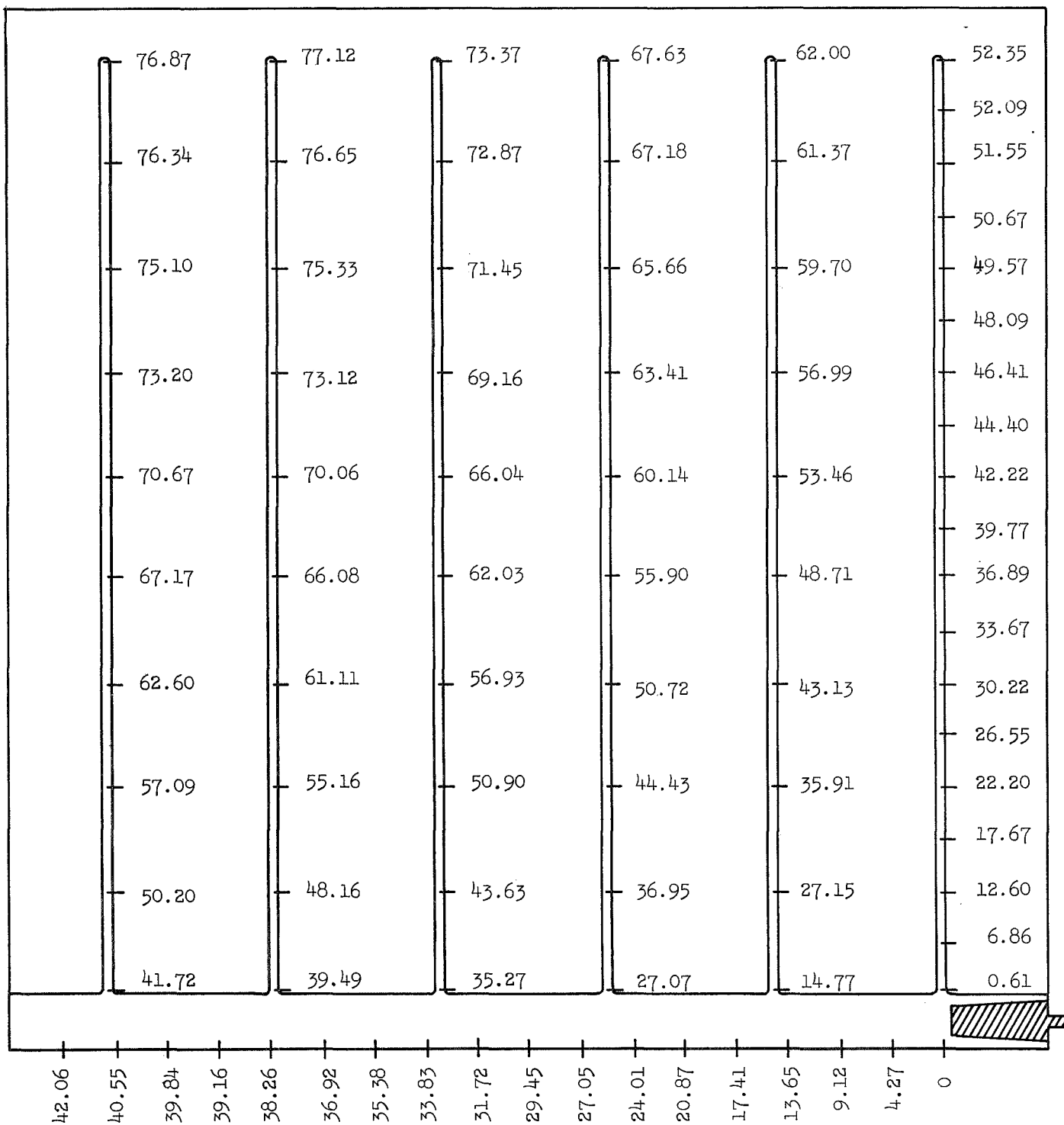


Figure 13 Potential profile of the Ti-Ag contacts with 1 A current flowing through the cell. The potential is measured with respect to the soldered lead.

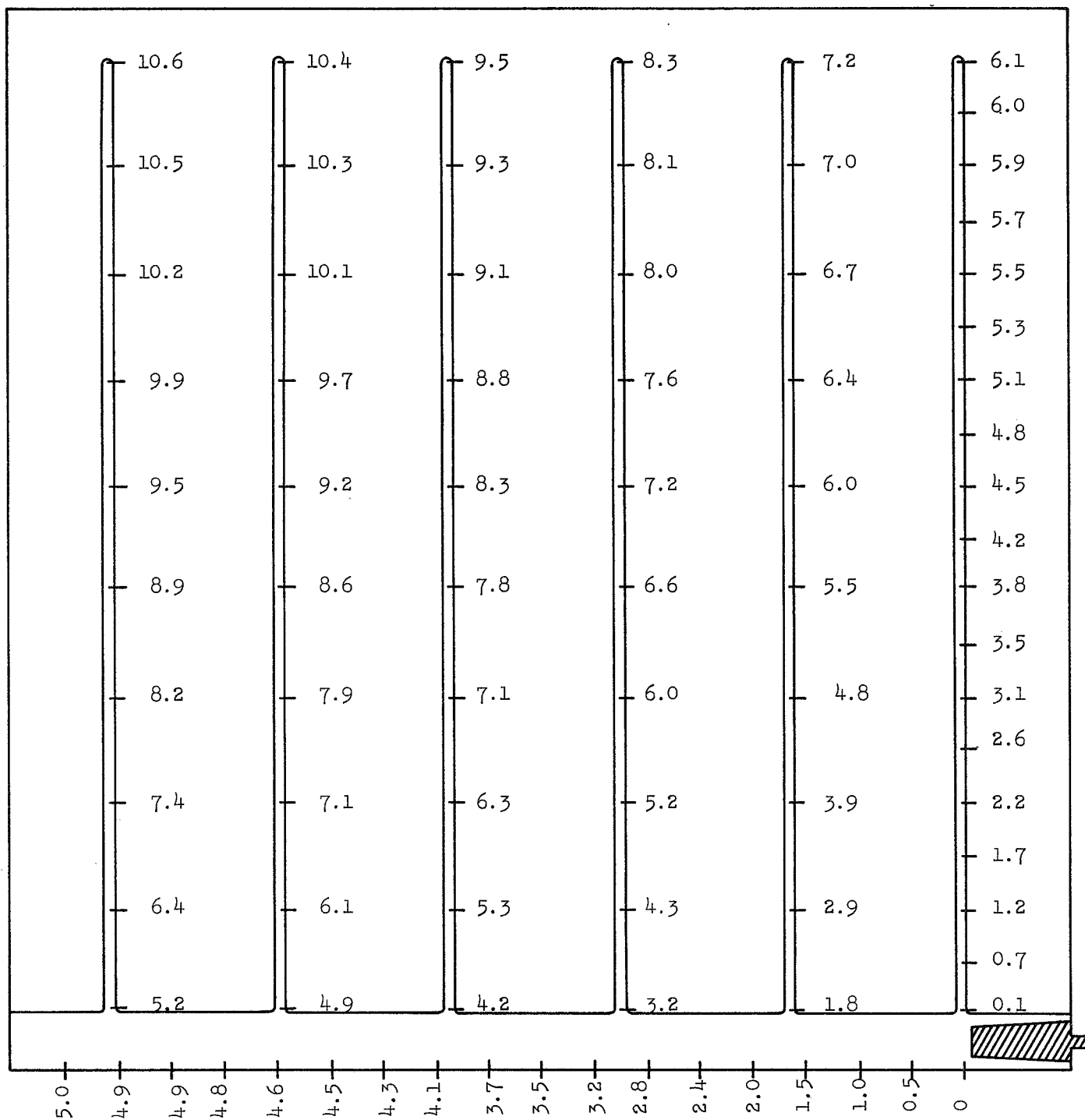
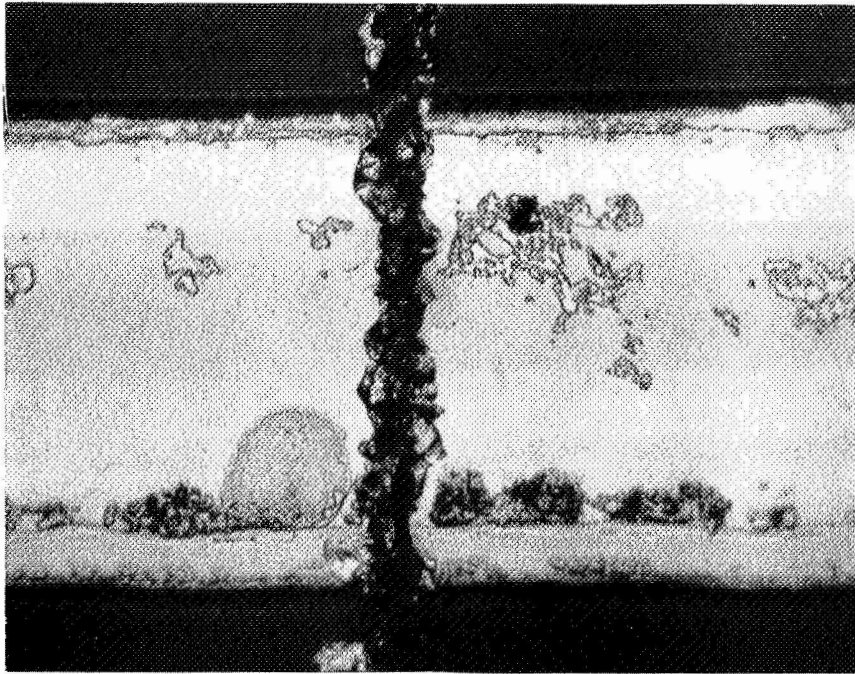


Figure 14 Potential profile of the Ti-Ag contacts with 100 mA current flowing through the cell. The potential is measured with respect to the soldered lead shown at the lower right.

(a)



(b)

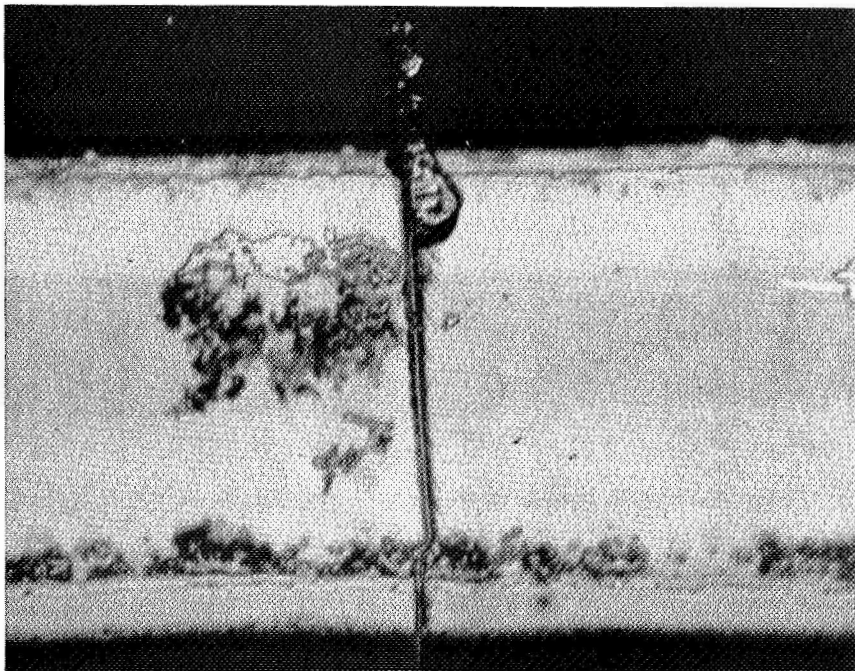
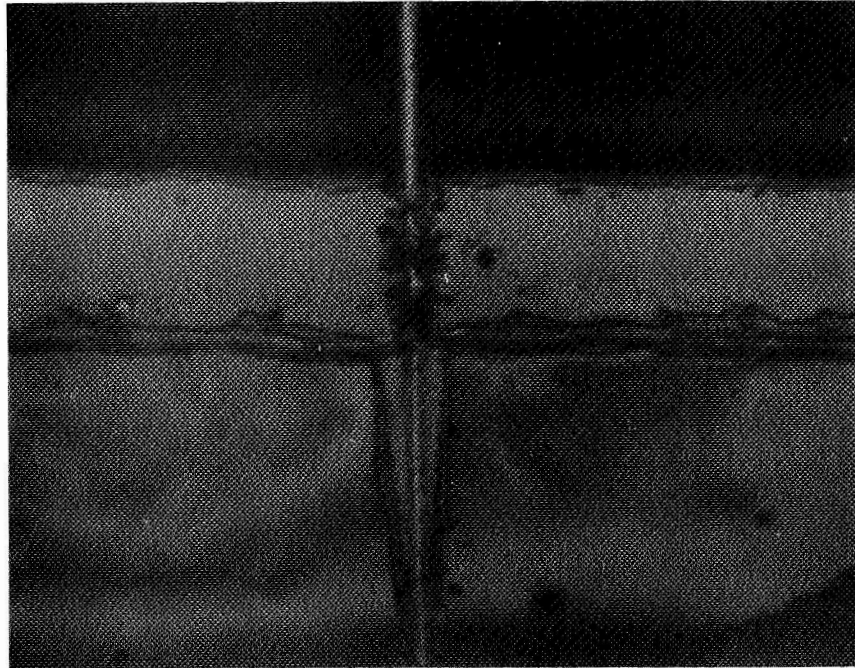


Figure 15 A diamond scribe line traversing a peeled grid line under (a) 50 g load, (b) 25 g load. Magnification is 150X.

(a)



(b)

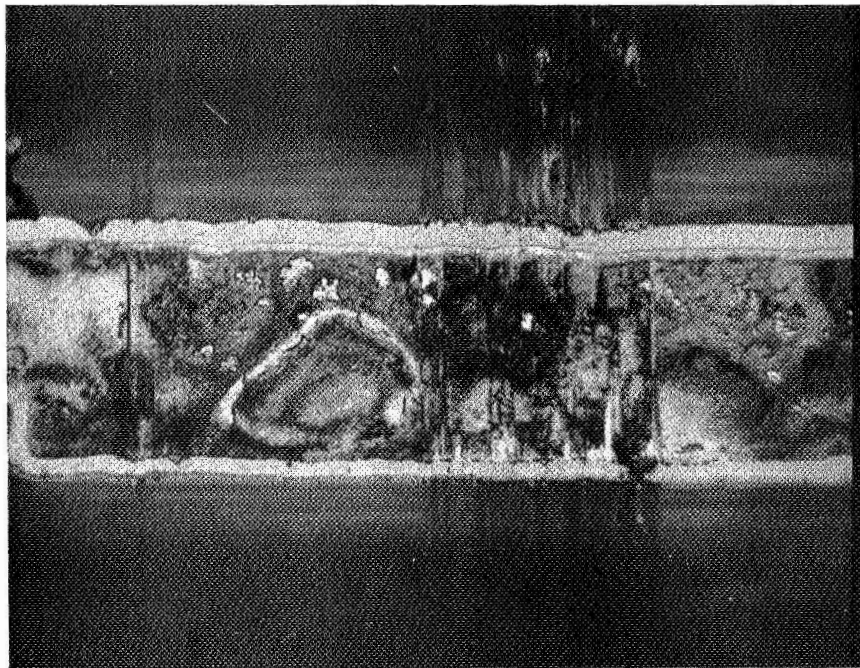


Figure 16 In (a) a diamond scribe line under 15 g load shows some folding back of the remanent contact material. Magnification is 320X. In (b) the effect of scribing a peeled cell with a W point under a 100 g load is shown. Magnification is 80X.

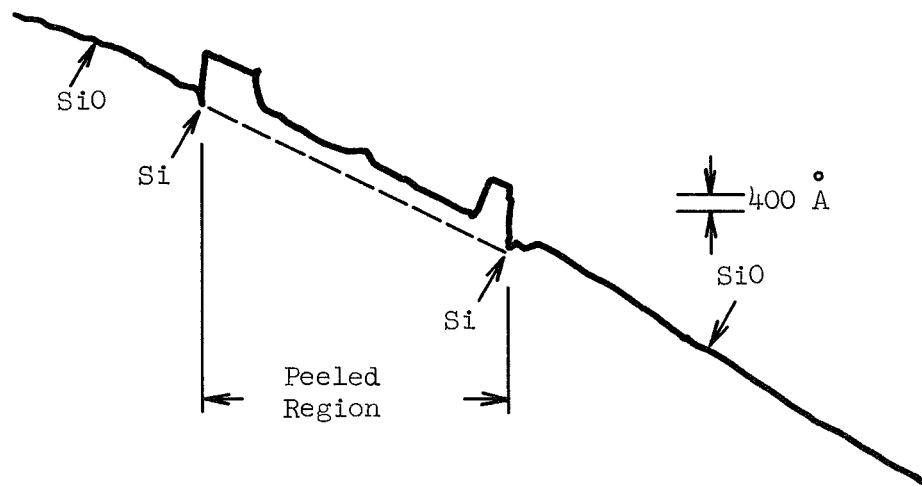


Figure 17 A Talysurf recording showing the surface relief feature of a peeled grid line. The dashed line is drawn in to show roughly the location of the Si-metal contact interface.

the photomicrographs of Figures 15 and 16. This behavior may at least be explained in part by the fact that the Ti layer tends to be drawn in at the edge of the contact, as pointed out earlier. The thickness of the residual contact material varies from roughly 500 Å in the central region to roughly 1500 Å at the edge.

I-V Characteristics.— I-V characteristics were recorded on several cells which had their Ti-Ag contacts intact. The I-V characteristics did not show any unusual behavior and the effective series resistance was low ( $<1\ \Omega$ ).

Power Dissipation Experiments.— It was the purpose of this study to note any unusual heating effects when a large forward current was caused to flow through the cell. A localized region exhibiting an abnormally large resistance to current flow would give Joulean heating. Some cells were coated with a temperature-sensitive paint (Detecto Temperature Paint No. 915-0900) while others were immersed in water or alcohol. In the former case, excessive heating was noted by the change in color of the coating (pink to blue) and the latter case by the appearance of bubbles that form on the cell. A forward current of the order of 5 to 10 A was used. Excessive heating almost invariably occurred in the vicinity of the ohmic strip contact. In a few cases heating appeared along the grid lines and extreme edge of the cell. These results do not imply that abnormally high resistance occurs in the vicinity of the ohmic strip contact, because the current is a maximum in this region. Hence it is felt that this study did not reveal any abnormal behavior.



### SECTION III

#### New Technology

All the research tools and techniques employed in, this study program to date are not new technology developed under this contract and therefore there is none to report here.

## SECTION IV

### Program for the Next Reporting Period

The program for the second quarter of Contract NAS5-11595 will very likely include:

- 1) Auger/LEED studies on Ti-Ag contacts as prepared by sputter-stripping treatments and on a peeled interface as prepared by peeling a contact just prior to placing in the ultrahigh-vacuum system.
- 2) EMM inspection of sectioned cells.
- 3) Potential probing of sectioned cells.
- 4) Preparation of Ti films on Si substrates with possibly Ag overlayers for the purpose of evaluating the effects of high humidity and temperature on the property of these films.
- 5) Initiate sputter-deposition of Ti and Ag (and possibly other metal combinations) on Si substrates and on Si solar cell blanks as described in Task 3 of the Technical Proposal No. TP-3074.
- 6) Other related studies including addition scribing experiments and electron microprobe analysis.

## SECTION V

### Conclusions

It has become apparent during the first three-month study program that contact degradation proceeds from within the Ti-Ag contact and that contact separation occurs somewhere in the vicinity of the Ti-Ag interfacial region, although not sharply defined. Interference colors found on the peeled interface suggest that some relatively transparent compound, as yet to be identified, has formed in this critical region and this is very likely a compound of Ti, as this element is known to be highly reactive. X-ray diffraction studies were not successful in detecting any well-crystallized intermetallic compounds or oxides, nitrides, etc., and this negative result suggests that the compound exists in an amorphous state. The compound in question appears to have insulating-like properties as shown by EMM inspection. This property has not been revealed in the few electrical measurements conducted in this laboratory, although detailed studies performed at NASA-Goddard laboratories have revealed an increase in cell series resistance with contact degradation.

One of the prime objectives of forthcoming studies will be to identify the atomic constituents in the region of contact separation. We are hopeful that Auger spectroscopy will single out a foreign constituent such as oxygen, nitrogen, or possibly hydrogen.

## SECTION VI

### Bibliography

1. L. A. Harris. Analysis of materials by electron-excited Auger electrons. J. Appl. Phys. 39: 1419-1427 (1968).
2. R. E. Weber and W. T. Peria. Use of LEED apparatus for the detection and identification of surface contaminants. J. Appl. Phys. 38: 4355-4358 (1967).
3. P. W. Palmberg and T. N. Rhodin. Auger electron spectroscopy of fcc metal surfaces. J. Appl. Phys. 39: 2425-2432 (1968).